A bottom-up method for evaluating the whole energy demand of large residential building stocks: an application to a regional scale.

L. Filogamo*, G. Peri, G. Rizzo
Department of Energy, Information Engineering and Mathematics Modelling (DEIM)
University of Palermo, Sicily, Italy
e–mail: luana.filogamo@unipa.it
filogamo@libero.it

A. Giaccone
National Research Council of Italy (CNR)
e–mail: giaccone@dream.unipa.it

ABSTRACT

In this paper a method is described, originally conceived during the compilation of the Energy and Environmental Regional Plan of Sicily, aimed to:

a) set up a lay-out model of an overall regional residential estate into a certain number of different building and heating system types;
b) calculate the energy needs of every single type according to the procedures established by the national and European regulations;

The method is particularly designed to evaluate the possible energy savings from the implementation of different interventions concerning the envelope and the HVAC systems to the various building types.
The method, although based on several assumptions, shows to be reliable enough and is also characterized by a simple structure easily adoptable by planners and technicians in their attempt to lead regional energy policies toward more sustainable paths.
The method has been validated against the aggregate value of the real energy demand deriving from the regional energy balance.

KEYWORDS

Buildings; energy demand; heating; cooling; appliances; regional masterplan; energy policy

1. INTRODUCTION

The need to manage national policies for energy production and supply and for environmental preservation [1, 2] has made the compilation of energy plans at a different territorial level (national, regional, municipal) a very common practice. In Italy, for example, the elaboration of regional and municipal energy plans is prescribed by the Law no. 10 dated 1991 [3].
Such plans need, first of all, a very accurate recognition of the real energy consumptions in the different sectors (industry, agriculture, transports, tertiary, residential) contributing to the overall energy demand of that territory.
Current data show that the energy demand of the European Union countries tends to split into three almost equal parts: one third for the industry and agricultural sector, one third for

* L.Filogamo (Corresponding authors)

transports and one third for the civil sector (tertiary and residential), the last one showing an increasing trend.
Despite the continuous spreading of tertiary, moreover, the residential sector is still prevailing inside the civil sector and is responsible of about 20 to 25% of the overall energy demand. This is a quite remarkable amount and shows the importance of the residential sector as regards energy planning.
On the other hand, the main objective of energy plans is the drawing up of different action scenarios aimed at the reduction of the energy demand and the correct use of the available energy sources.
In order to better evaluate the adequacy of each proposed action, the future energy demand has to be disaggregated with regards both to energy sources employed and to end uses until every single cause of consumption is singled out.
As for the residential sector, this analysis may be very difficult due to the huge splitting of the building stock into buildings and single housing units, and to the lack of detailed information about such a wide and inhomogeneous set of samples to be investigated.
Below a procedure is described, developed and applied for the analysis of the residential energy demand of Sicily, that with its 1,717,000 dwelling units, constitutes one of the larger and populated regions of Italy. This procedure, that can represent the basis for future energy scenarios, shows an easy applicability to other regional contexts.

2. TYPOLOGICAL CLASSIFICATION OF BUILDINGS

Final energy uses in the residential sector are generally referable to the several tasks, such as: space heating, space cooling, indoor lighting, domestic hot water production, cooking, electric appliances.

Of all these uses, winter heating and summer cooling of indoor spaces, while representing the most relevant part of the energy demand of a building, are depending on complex factors as:

- the geometrical and thermo-physical characteristics of buildings;
- the heating and cooling system type;
- the site localization of buildings.

In other words, for an accurate analysis of the energy demand of the residential sector and of the achievable energy savings, the mere determination of the overall number and volume of a whole building stock is not sufficient.
In Italy, as in most other countries, such data are collected with a decade-long cadence through the General Survey of Population and Housing by the National Institute of Statistics (ISTAT).
In the following paragraphs the use of these data is shown with regards to the case of Sicily.

2.1 Building types

Each building is classified by ISTAT [4] with regards to the following features:

- number of building floors;
- number of dwellings in the building;
- contiguousness with other buildings.

On this base, twelve different geometrical typologies have been identified [5], whose description and schematization is reported in Figure 1.

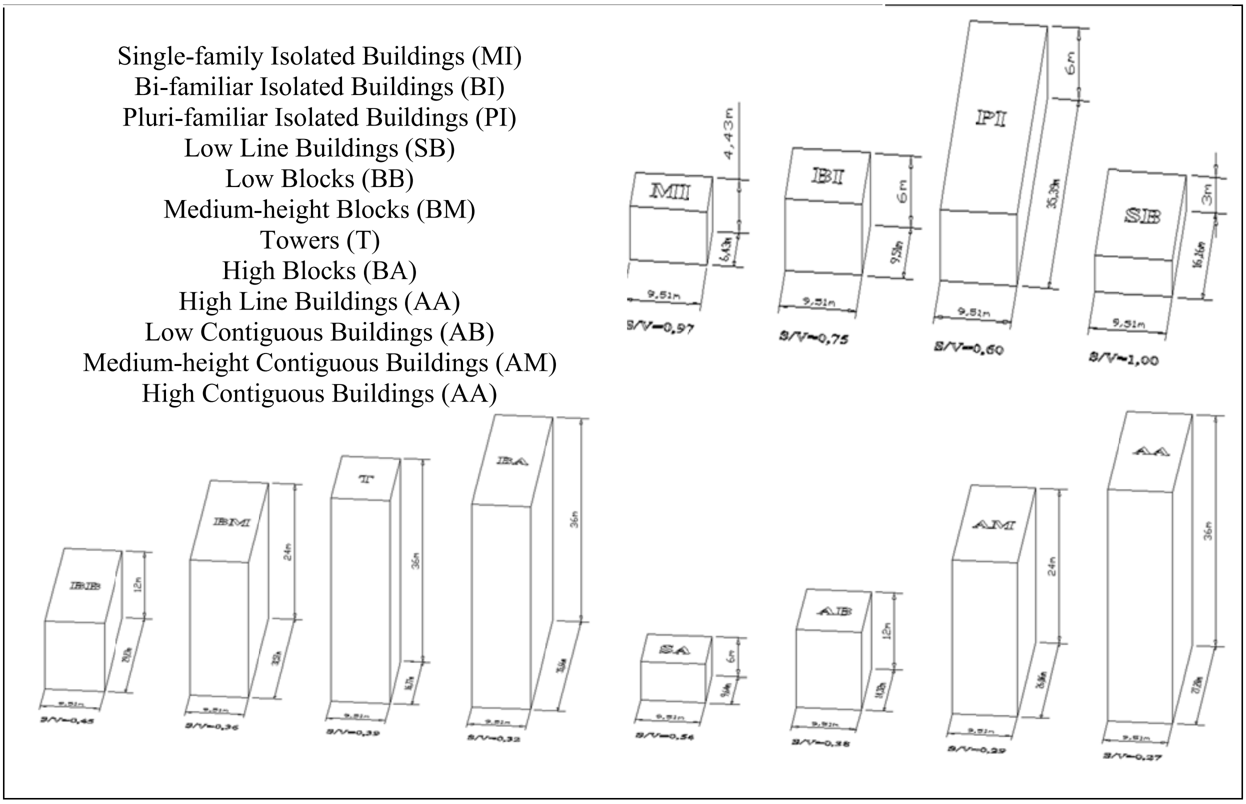

Figure 1. Description and schematic representation of the main typologies constituting the Sicilian regional building stock

In Tables 1a and 1b are also reported the main features of the selected typologies, starting from which the bottom-up deriving of the whole residential energy demand is made.

Table 1a. Main features of typologies referring to isolated buildings

Floors	Dwellings						
	1	2	3 - 4	5 - 8	9 - 15	16 - 30	>30
1	Single-family Isolated Buildings	Bi-familiar Isolated Buildings	Low Line Buildings				
2			Pluri-familiar Isolated Buildings				
3-5			Low blocks				
6-10			Medium-height blocks				
>10	/	/		/	Towers		High blocks

Table 1b. Main features of typologies referring to contiguous buildings

	Dwellings						
Floors	1	2	3 - 4	5 - 8	9 - 15	16 - 30	>30
1				Low Line Buildings			
2				High Line Buildings			
3-5	/				Low Contiguous Buildings		
6-10		/				Medium-height Contiguous Buildings	
>10		/				High Contiguous Buildings	

In Table 2 the number of dwelling units for each typology is shown, according to the ISTAT survey [6].

Table 2. Number of dwellings for each building type and pertinent percentage

Building type	Number of dwelling units	Percentage
Single-family Isolated Buildings (MI)	173200	10.1
Bi-familiar Isolated Buildings (BI)	38400	2.2
Pluri-familiar Isolated Buildings (PI)	27300	1.5
Low Line Buildings (SB)	307200	17.9
Low Blocks (BB)	119400	7.0
Medium-height Blocks (BM)	70000	4.1
Towers (T)	2400	0.1
High Blocks (BA)	6900	0.4
High Line Buildings (AA)	382000	22.2
Low Contiguous Buildings (AB)	437800	25.4
Medium-height Contiguous Buildings (AM)	139500	8.1
High Contiguous Buildings (AA)	13000	0.8
Total	1717100	100.0

2.2 Geometrical properties

For each geometrical typology, the average number of floors and dwellings and the peculiar dimensions (width, L, depth, P and height, H) of the building have been defined and the value of the so-called “shape ratio” S/V, i.e. the ratio between the external building surface S and its heated volume V, has been also evaluated.

To do this, a building has been assumed to be a parallelepiped resulting from the aggregation of a certain number of dwelling units, each of them having a square plan equal to 90.48 m^2, that is the average plan area of a dwelling unit as noted by the ISTAT survey [6], and a typical floor height of 3 m, leading to a dwelling volume of 271.44 m^3.

Moreover, since each dwelling unit is composed, on the average, by 4 rooms plus 1 bathroom, a typical area of the window surface can be defined as equal to 8.82 m^2 per dwelling, according to the Italian standard for the light in residential buildings.

On the basis of this simplifying scheme, the overall glazing area S_g, the external wall area S_w and the roof area S_r of each building type have been calculated.

In Table 3 average geometrical properties of each building typology are shown.

Table 3. Mean geometrical properties of selected building types

Building type	Floors	Dwellings	H	L	P	S	V	S/V	Sw	Sg	Sr
MI	1.5	1.00	4.4	6.4	9.51	263.7	271.3	0.9	132.5	8.8	61.1
BI	2	2.00	6.0	9.5	9.51	409.1	542.6	0.7	210.6	17.6	90.4
PI	2	7.00	6.0	35.3	9.51	1212.0	2019.5	0.6	473.1	65.6	336.5
SB	1	2.00	3.0	16.1	9.51	461.2	460.9	1.0	139.0	14.9	153.6
BB	4	12.00	12.0	29.2	9.5	1487.3	3340.1	0.4	822.1	108.5	278.3
BM	8	26.00	24.0	31.5	9.5	2572.1	7204.9	0.3	1737.4	234.2	300.2
T	12	21.00	36.0	16.7	9.5	2211.5	5742.9	0.3	1705.8	186.6	159.5
BA	12	45.00	36.0	35.6	9.5	3930.7	12209	0.3	2855.5	396.9	339.1
SA	2	2.00	6.0	9.6	9.5	299.0	549.9	0.5	97.7	17.8	91.6
AB	4	6.00	12.0	14.3	9.5	616.2	1634.7	0.3	290.6	53.1	136.2
AM	8	22.00	24.0	26.0	9.5	1746.2	5946.9	0.2	1057.3	193.3	247.7
AA	12	34.00	36.0	27.2	9.5	2483.0	9339.6	0.2	1660.5	303.6	259.4

2.3 Thermo-physical properties

The ISTAT survey differentiates buildings also with regards to the construction period and to their framework (masonry walls or reinforced concrete).

In this study, according with local design approach typically adopted by architects, it has been assumed that:
- masonry frame walls have a density equal to 1900 kg/m^3, a thermal conductivity equal to 1.15 W/m K, and a thickness varying with the building height;
- enclosure walls of concrete frame buildings prior to 1971 are made by natural stone with a density equal to 1500 kg/m^3 and a thickness of 25 cm;
- enclosure walls of concrete frame buildings after 1971 are made by light concrete blocks with a thickness of 25 cm;
- for buildings built-up after 1981 double glazed windows are considered with a thermal transmittance equal to 3 W/m^2 K, while for buildings prior to 1981 single glazed windows with a thermal transmittance equal to 5 W/m^2 K; due to the presence of shutters, according to national regulations, the overall thermal day-night transmittances becomes 2.5 W/m^2 °Kfor double glazed windows, 4 W/m^2 K for single glazed windows;
- thermal transmittance of roofs has been assumed equal to 0.5 W/m^2 K for buildings prior to 1945 in small towns with less than 20,000 people, due to the usual presence, in such situations, of unheated attics directly under the tilted roof; otherwise a transmittance equal to 1.7 W/m^2 K has been assumed;
- thermal transmittance of ground floors has been assumed equal to 0.65 W/m^2 K whether they are conterminous with unheated basement spaces or built upon a rock and gravel bed.

2.4 Heating system types

The survey differentiates the building heating systems with regards to energy source (solid, liquid or gaseous fuel, electric energy) and heat supply mode (central system, autonomous dwelling systems, individual stand-alone heaters).

In Table 4 the distribution of dwelling units in Sicily according to energy source and heat supply mode is shown: it has to be noted that about the 53% of dwellings do not have installed a proper heating system.

Table 4. Number of dwellings for energy source and heat supply mode

Heating system	Liquid fuel	Solid fuel	Gaseous fuel	Electric	Others	Unknown
Central	154400	3300	29000	7800	1000	2500
Autonomous	61300	10200	131100	30900	3400	2000
Stand-alone equipments heating the whole dwelling	15700	43700	24900	76500	4300	2100
Stand-alone equipments heating parts of the dwelling	9900	59000	31700	85900	4600	2800
No heating system			908700			

However, national regulations about heating calculations distinguish heating installations between two main categories: combustion systems and heat pump systems.

According to these indications, survey data were rearranged, as shown in Table 5, introducing nine different heating system types.

Table 5. Number of dwellings for heating system type

Heating system type	No. of dwellings	Percentage
Central combustion systems	190100	11.1
Central heat pump systems	7900	0.5
Autonomous combustion systems	207300	12.1
Autonomous heat pump systems	31600	1.9
Fixed combustion heaters	87700	5.1
Fixed single-room combustion heaters	104600	6.1
Single-room heat pumps	124200	7.3
Mobile combustion equipments	490200	28.7
Mobile electric equipments	463200	27.1

It has been here assumed that dwelling units for which no heating system has been declared in the survey, actually are heated as well through mobile equipments (stoves) covering part of the heating load of the dwelling.

2.5 Geographical localization of buildings

For the purpose of energy calculations, regulations suitably subdivide Italian country in six climatic zones with regards to their heating degree-days [7].

Table 6 shows the distribution of Sicilian dwelling units between the different climatic zones (see also Figure 2); it has to be noted that the 98% of dwellings are included in the B, C and D climatic zones, while less than 1% is included in zones A and F.

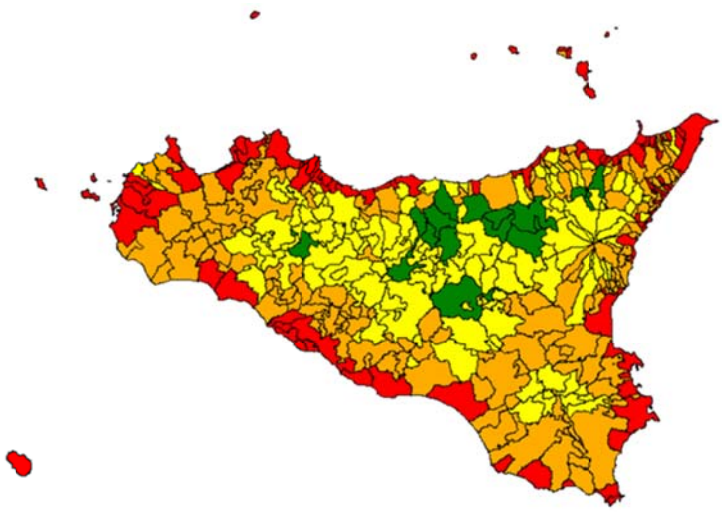

Figure 2. Subdivision of the Sicilian territory in climatic zones characterized by the degree days number.

Table 6. Percentage of dwellings for each climatic zone

Climatic zone	A-B	C	D	E-F
Degree-days	766	1150	1649	2250
Dwelling units (%)	0.51	0.33	0.14	0.02

For each climatic zone the weighted average value of degree-days is also shown in Table 7, while in Table 8 are reported average values of temperature and solar radiation used in calculations.

Table. 7. Average outdoor temperatures [°C] for each climatic zone

Zone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Zones A-B	11.0	11.4	13.0	15.4	18.9	23.0	25.9	25.9	23.8	19.8	16.0	12.6
Zone C	9.8	10.4	12.4	15.3	19.7	24.8	27.8	27.6	24.4	19.6	15.5	11.3
Zone D	6.8	7.4	9.5	12.7	16.9	22.1	25.3	24.8	21.7	16.9	12.4	8.5
Zone E-F	4.1	4.7	6.7	10.3	14.5	20.2	23.5	22.8	19.5	14.1	9.4	6.0

Table. 8. Average daily solar radiations [MJ/m2]

Orientaion	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Horizontal	8.2	11.4	15.9	20.9	25.3	27.9	27.9	25.3	19.7	13.7	9.6	7.3
Vertical W-E	6.2	8.3	11.1	13.8	16.2	17.5	17.7	16.6	13.6	10.0	7.3	5.6
Vertical N	2.5	3.3	4.3	5.9	8.5	10.3	9.5	6.8	4.6	3.6	2.7	2.2
Vertical S	11.7	12.7	12.5	10.8	9.3	8.5	9.0	11.1	13.4	14.2	13.6	10.8

3. ENERGY DEMAND CALCULATION

The procedures suggested by the national and European regulations on residential heating demand calculations [8], basically referring to the widely accepted method of the “utilization factors”, have been applied to each building type with their assigned geometrical and thermo-physical properties for each heating system type and climatic zone.

According to this method, the heating energy demand Q is calculated as:

$$Q=Q_1 - u_g * Q_g \tag{1}$$

where:

Q_1 are thermal losses, for transmission and ventilation (W);

Q_g are thermal gains, solar and internal (W);

u_g is an “utilization factor” of thermal gains, due to the thermal inertia of the building (dimensionless).

The resulting heat demands have been summed up to find the overall heating demand of the whole regional building stock, which is shown in Table 9, where they are subdivided into different heating system type and climatic zones. As it is reported in Table 9, combustion and electric heat pump systems are contemplated for winter heating.

The calculation of the energy demand for cooling does require a more accurate analysis, since unsteady state phenomena are in this case involved, mainly due to the important role played by the solar radiation hitting and entering the building envelope.

Table. 9. Primary energy demand for winter heating [ktoe]

Climatic zone	Combustion systems	Electric heat pump systems	Total
A-B	213	91	304
C	147	92	239
D	120	68	188
E-F	23	13	36
Total	503	264	767

An estimation of the summer cooling demand has also been performed through a simplified method proposed by Kusuda [9] allowing a calculation for every monthly average day based on average transmittances of buildings and sol-air temperatures.
According to this method, the energy, E_0 (J), flowing through a wall in a certain time T, assuming that the variation of its internal energy is negligible, can be calculated as:

$$E_0 = f_c\ K_0\ S_0(\theta_i - \theta_0)T \tag{2}$$

where:
S_0 is the wall surface (m^2);
K_o is the thermal transmittance of the external wall ($W/m^2 K$);
θ_o is the sol-air temperature (K);
T is the time (s);
f_c is a factor taking into account the variation of the indoor adduction coefficient, equal to:

$$f_c = 1 - 0.194\ K_m + 0.021\ K_m^2 \tag{3}$$

where:
Km is the average thermal transmittance of the building ($W/m^2 K$);
θ_o is equal to:

$$\theta_0 = \theta_e + \frac{\alpha I}{h_e} \tag{4}$$

θ_e is the average outdoor temperature (K);
α is the global hemispheric absorption coefficient of the wall;
I is the average solar irradiation on the wall (W/m^2);
h_e is the outdoor adduction coefficient($W/m^2 K$.

The ISTAT survey shows that only the 20% of Sicilian dwellings is actually provided with proper cooling systems (air conditioning systems), even if the number is rapidly increasing in the last years.
In this study it has been assumed that the remaining part of the building stock resorts to electric ventilators to secure air movement during summer.
The overall demand of primary energy for summer cooling under these assumptions is shown in Table 10.

Table. 10. Primary energy demand for summer cooling [ktoe]

Climatic zones	A-B	C	D	E-F	Total
Ventilators	24.94	16.34	5.30	0.49	47.07
Air conditioners	7.85	9.06	1.73	0.09	18.73
Total	32.79	25.40	7.03	0.58	65.80

As for the remaining energy demand (lighting, cooking, domestic hot water, electric appliances), it can be estimated in an average of 0,390 kW/m^2. Concerning only the internal gains, this value is computed on the basis of the method suggested by the currently in force regulation in Italy, where these contribution to the whole energy balance of a building are estimated with the relation described in Equation (5).

$$\emptyset_{int} = 5.294 \cdot A_f - 0.01557 \cdot {A_f}^2 \tag{5}$$

where A_f is the net floor area (m^2).

In conclusions, our estimation concerning only the heating and cooling purposes, shows a whole value of 833 ktoe, as the summation of winter (767 ktoe) and summer (66 ktoe) energy demands. At this stage, since our main purpose was to present a bottom-up method aimed at usefully disaggregating the whole regional building park, we did not proceed with the estimation of energy needs referring to indoor appliances and lighting. These estimations, in fact, deeply apply to considerations based on the behaviours of people and on the main GDP of the involved population. This analysis is presently under study, in order of totally reconstructing the building energy demand by typologies.
Anyway, it is worthy here remembering that, real energy demand data, as collected in Italy by the "Italian Agency for the New Technology, the Energy and the Environment" and published through yearly Regional Energy Balances [10], shows a value for residential purposes close to 900 ktoe/y, that is with acceptable accordance compared to the findings of our analysis.

4. DISCUSSION

The previously cited procedure, based on a suitable disaggregation of the whole regional building stock, can be assumed as the starting point for possible scenarios concerning the future energy uses in a given regional territory. By the way, this method, as applied during the preparation of the Regional Energy and Environmental Master Plan, has shown a reasonable reliability: for example, in the case of the electric energy consumptions, a comparison between such disaggregated calculation (5385 GWh) and the whole consumption reported by the official energy balance [10] of Sicily (5400 GWh), resulted in an very good matching, since both values diverged only for a difference less than 1%.

Such a detailed analysis is now allowing to calculate the effects of different saving actions on the final energy demand of the building stock.
Staring from the proposed disaggregation, in fact, thermo-physical properties can be usefully modified in order to take into account the effects of thermal insulation on the vertical walls of the building envelope or other parts of it, for example those oriented to the north, for all the building stock or only some specific building types in some specific climatic zones.
In the same way, the replacement of single glazed windows with double glazed windows or actions on the heating system can be easily analyzed.

As that, new results for the heating demand can be calculated for each possible saving action and each action matched with the others in order to found out the most promising ones, in this way proposing a sort of regional energy scenario for the given region.
The method resulted in some relevant indicators for Sicily, like, for example:

- an energy demand reduction of about 20% is attainable by a proper thermal insulation of roofs;
- an energy demand reduction of about 6% is attainable by the replacement of single glazed windows;
- an energy demand reduction of about 25% is attainable by the replacement of old boilers.

5. CONCLUSIONS

Regional energy balances compiled through real yearly data coming from energy producers and suppliers provide energy planners with overall values for thermal and electrical energy demand of the industrial, transport, civil and residential sectors.
As regards, in particular, the residential sector such overall values do not allow to estimate the specific contribution of every different building type (single buildings, line buildings, blocks, towers), of every different heating system type (central or self-standing, boiler or heat pump, fuel fired or electric) and of every part of the building-plant system (walls, roofs, glazed surfaces, heat generation, distribution and regulation systems). This represent an important limit for the evaluation of the relative effectiveness of different possible actions (thermal insulation, heating system improvement or substitution, etc.) to reduce the demand.
The study here described demonstrates how it is possible to use general survey data in order to overcome such inconveniences, by building-up a disaggregated equivalent structure of the building stock into a certain number of representative typologies.

REFERENCES

1. Franzitta, V., La Gennusa, M., Peri, G., Rizzo, G., Scaccianoce, G. Toward a European Eco-label brand for residential buildings: Holistic or by-components approaches? (2011) *Energy*, 36(4), pp. 1884-1892.
2. Peri, G., Rizzo, G. The overall classification of residential buildings: Possible role of tourist EU Ecolabel award scheme (2012), Building and Environment, 56, pp. 151-161.
3. LEGGE 9 gennaio 1991, n. 10. Norme per l'attuazione del Piano energetico nazionale in materia di uso razionale dell'energia, di risparmio energetico e di sviluppo delle fonti rinnovabili di energia. G.U. n. 13, 16-01-1991. Rome. (*in Italian*).
4. Corrado V., Ballarini I., Corgnati S.P., Tatà N., Building typology brochure – Italy, (2011) Politecnico di Torino – Dipartimento di Energetica, Gruppo di ricerca TEBE.
5. Regione Siciliana, Giunta Regionale, Deliberazione n°1 del 3 febbraio 2009. "Piano Energetico Ambientale Regionale Siciliano P.E.A.R.S.
6. http://www.istat.it/it/archivio/3758
7. Legge 26 agosto 1993, n. 412, articolo 1, Norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia, (*in Italian*).
8. ISO 13790:2008, Energy performance of buildings -- Calculation of energy use for space heating and cooling, International Standard Organization, 2008, Geneva.
9. Kusuda T., NBSLD, The computer program for heating and cooling loads in buildings, NBS, Building Science Series n° 69, Washington (DC), 1976.
10. Regione Siciliana, Assessorato Energia e Servizi di Pubblica Utilità, Dipartimento dell'Energia, Servizio II. Bilancio Energetico Regionale, 2008.